NASA TT F-11,061

NASA TT F-11,061

THE CIRCULATION UNDER EXPOSURE TO ACCELERATION. X-RAY PHOTOGRAPHY ON MONKEYS

U. Fischer

Translation of "Der Kreislauf unter Beschleunigung. Röntgenaufnahem beim Affen." Luftfahetmedizin, vol. 2, pp. 1-13, 1938.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D. C. 20546 June 1967

NASA TT F-11,061

THE CIRCULATION UNDER EXPOSURE TO ACCLERATION. X-RAY PHOTOGRAPHY ON MONKEYS*

U. Fischer

(from the Aeromedical Research Institute of the National Air Ministry, Berlin.)

ABSTRACT. Acceleration experiments were performed on monkeys using a centrifuge; thorotrast was injected and x-ray photographs were taken during the accelerations. It was found that when centrifugal force acts in the head-to-leg direction, heart filling decreases as acceleration increases. The heart was nearly empty at 4.4 G. The aorta and vena cava decrease in diameter as the heart empties. At 3.3 G, the heart requires several minutes to become empty; at 4.4 G, it is empty in a few seconds. The duration of acceleration also has an effect on heart filling. When the centrifugal force acts in the stomach-to-back direction, heart filling remains good even at high, prolonged acceleration.

INTRODUCTION

During actual aircraft flights the phenomenon has been observed that when there is acceleration of a certain G number (G=1 earth acceleration force) the circulation fails (a black curtain before the eyes) [1]. Assistant Doctor Bührlen has confirmed these phenomena observed in practice during his acceleration experiments using humans as experimental subjects in the centrifuge of the Aeromedical Research Institute. In his experiments, he was further able to confirm the previously expressed assumption[1] that the ability to endure acceleration (acceleration tolerance) depends on the position of the subject in relation to the axis of rotation and therefore on the direction in which the centrifugal forces act. Thus he was able to establish that, when the centrifugal forces act in the stomach-to-back direction, higher accelerations can be tolerated than when the centrifugal forces act in the head-to-leg direction. If these phenomena are to be investigated further, the next question is: how does the circulation failure occur? There are two possible explanations for this: /1**

1. The necessary height of pressure is not present, i.e., the force of the filled heart is not extensive enough to force the blood up to the brain against the hydrostatic pressure caused by the counteracting centrifugal forces[2].

* Dissertation of the Medical Department, University of Berlin.
**Numbers in the margin indicate pagination in the foreign text.

2. The heart generally does not have enough blood to provide satisfactory supply to the brain since the far greater part of the blood has been forced into the lower regions of the body by the centrifugal forces acting in the head-to-leg direction, as was conjectured by Jongbloed and Noyons and as proven in rabbits[3].

If the second explanation is assumed to be correct, that the lack of blood resulting from the concentration of blood (in the lower regions) caused the circulation failure, then another question arises: does the increased tolerance of higher accelerations have its basis in the fact that the heart is better filled, when the centrifugal forces act in the stomach-to-back direction.

For all these possibilities and considerations, the question of filling naturally does not solely concern the heart but also the aorta, vena cava, and lungs.

To investigate this question, on the instigation of Staff Physician Dr. Otto F. Ranke, 12 animal experiments were performed using the centrifuge of the Aeromedical Research Institute--10 of them with monkeys (Macacus rhesus) and one each with a dog and rabbit; 128 x-ray photographs were made; 104 of the monkeys, 13 of the dog, and 11 of the rabbit.

EXPERIMENTAL PLAN

Roentgen-photography is the most suitable means of performing such experiments. The experimental animal is injected with a suitable x-ray contrast medium and its circulation during any desired stage of the experiment can then be checked and observed by means of the x-ray photographs. /2

The monkey has been shown to be the most suitable experimental animal; its thorax is very similar to that of a human in its shape, its spinal column is sufficiently stable to tolerate higher accelerations without severe bending.

Figure 1 shows the photograph of a monkey at an acceleration of 2.2 G. The spinal column is only slightly bent whereas the bending of the rabbit shown in Figure 2 is quite noticeable. Due to its living habits and its rapid and powerful movements, the monkey has good circulation control.[4] In contrast to the monkey, the dog and rabbit either do not possess these properties, or have them to only a slight extent. For example, it is only necessary to keep a rabbit on its hind legs for a brief period of time in order to cause peripheral pooling of the blood and thereby a circulation failure[5]. Experiments with both the rabbit and dog are completely unsuited for comparisons with humans for our purposes. Also the size of the monkey, particularly Macacus rhesus, makes it especially suited for these experiments, since the dimensions of the centrifuge are considerably more adaptable to it, than to a human. The ratio of body size to the heart-axis distance is 0.86 for humans; for the monkey, on the other hand, it is only 0.26.

The thorium preparation, thorotrast, made by the firm of Heyden, Radebeue-Dresden was injected in large amounts. Thorotrast makes the entire circulation roentgenologically visible for 1 to 2 hours before it accumulates in the liver and spleen. It mixes with the blood without precipitating, causes no clots, /3

Figure 1

Figure 2

Figures 1 and 2. Comparison of spinal columns
Figure 1 (Exp. 2/2) Acceleration 2.2 G, monkey, 2.5 kg under Pernokton narcosis
Figure 2 (Exp. 6/2) 2.2 G, rabbit, 2.3 kg, Pernokton narcosis

has approximately the same viscosity as blood, and does not irritate the vessel walls[6]. Due to these properties the experiment could be performed under near-normal physiological conditions.

The injection of large amounts of thorotrast into one of the larger veins of the body makes an operation necessary. necessary. For this reason, the monkey was anesthetized. Pernokton made by the firm I. D. Riedol, E. de Haen, A. G., Berlin, was used as an anesthetic. In order to exert the least possible effect on the physiological relationships during the experiments, the anesthesia was made as light as feasible. A dosage of 0.3 cc/kg body-weight was injected intramuscularly. If the anesthetic took too long to have an effect, small additional doses were given so that the total dose reached 0.35 to 0.45 cc/kg body-weight. The large veins of the throat are most suited for thorotrast injection. It is not advisable to inject into the thorax itself, since the x-ray photos will become unclear from the excess of thorotrast. The veins of the lower extremities are unsuited for injection because bleeding may occur in them as the result of exposure to centrifugal force. It was initially attempted to use the veins of the sulcus bicipitalis in the upper arm for injection, but this proved to be unsuitable since it is often hard to find, thus putting an extra strain on the test animal due to the additional length of time of the operation. In addition, the vessels are so small in this area that the injection of large amounts would be highly difficult.

In order to observe the behavior of the circulation, both during short and long-lasting accelerations, x-ray photos were taken of 2 animals, not only when the desired G-number had been reached in the centrifuge, but also after this acceleration had acted on the animal for a rather long period (1 to 2 min.).

Methodology. The test animal was mildly anesthetized with pernokton; after 1 to 1 1/4 hours, anesthesia was achieved and the monkey was tied to the test board.

The test board is around 30 x 80 cm. in size; it contains a depression (1) in the center which corresponds approximately to the sitting height and width of the test animal. On the right and left sides of the depression at the shoulder level is an outward-directed groove (2) for the upper extremities. Holes around the depression at the level of the upward-bent upper extremities and around the head area (3) ensure that the animal will remain tightly fastened. On the right side of the depression, there is a board (4) 10 cm. wide, at a right angle to the test board, which gives the animal the necessary support in the left side position, especially when the centrifugal forces act from the rear, thus hindering displacements and bendings. A seat board (5), which can be moved into the lower part of the depression, is held fast by a screw clamp (6), can be adjusted to the size of the test animal, and gives the animal support in this direction. /4

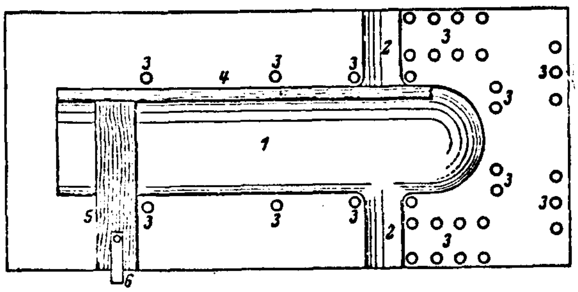

Figure 3. Test board

The animal was fastened in the back position on the test board. The head was held by a bridle fastened above, ensuring easy access to the area of the throat incision. Usually the internal jugular vein is exposed for 2 or 3 cm. For male monkeys the back-pouches subject to strong bleeding had to be circumvented. The peripheral end of the exposed segment of vein was tied off. A cannula was introduced into the central part and fastened with a ligature in order to avoid an air embolism. It is advisable to grind off the point of the cannula used for injection, in order to avoid penetrating the vessel wall during injection. The amount of thorotrast corresponding to body weight, 12 cc/kg, is injected at body temperature in a 100 to 200 second period; the central part of the vein is also tied off after the cannula is removed and the incision is clamped shut. The monkey, bound in the back position on the test board, is mounted on the centrifuge so that it lies with its head in the direction of the centrifuge axis, so that the centrifuge forces will act in the head-to-leg direction. The x-ray device is a Siemens-Veila megganos-device, a special modification as an acceleration resistant attachment, which was built according to the specifications and under the direction of Prof. Dr. Otto F. Ranke. Transformer and switch box are mounted near the axis. An insulated cable leads from the transformer to the tube. An AC voltage of 220 volts is placed across the two slip-rings. The time-switches are located on the control-panel of the centrifuge. The x-ray plate-holder lies on the seat-board of the centrifuge under the 1.2 cm thick test-board. It is held at chest level on the test board by a chock. The plate-holder must be changed after each frame, which involves stopping the centrifuge, and therby adds to experimental difficulty. The x-ray photos are taken in both the back- and left-side position, first when the centrifuge is standing still, later at accelerations of 2 to 7 G, and in some experiments 8.4 and 10 G. Pictures are taken when the position of the test animal changes in the direction in which the centrifugal forces act. The test board is rotated 90° in such a manner that the abdomen lies in the direction of the axis of rotation, causing the centrifugal forces to act in a stomach-to-back direction. In these experiments, the pictures are taken only from the left-side position and 0.5 to 0.6-second exposures are used, depending on the size of the test animal. Although these exposures are longer than a heart-period, the heart pictures on the x-ray film are not accidental hits, in in that the heart is sometimes taken in systole, sometimes in diastole, but rather average pictures are obtained which, though not very sharp, make it possible to make a comparison between them. The focus distance is 70 cm., 22 MA are sufficient for a complete photograph.

Since no further use of a given monkey is possible after the experiment, for humane reasons it is killed by suboccipital puncture while still under narcosis.

TABLE 1

Photograph number	Time of beginning of centrifuge operation	G number	G number attained after number of secs.	Duration of acceleration in sec.	film-exposure time	position
1	12.07		photo taken at rest		0.6	1st position back
2	12.09	2.2	30	instantaneous	0.6	1st position back
3	12.10	3.3	30	instantaneous	0.6	same
4	12.12	4,4	30	instantaneous	0.6	"
5	12.16		photo taken at rest		0.6	1st position left side
6	12.17	2.2	23	instantaneous	0.6	same
7	12.18	3.3	23	instantaneous	0.6	"
8	12.20	4.4	28	instantaneous	0.6	"
9	12.23		photo taken at rest		0.6	2nd position left side
10	12.24	2.2	26	instantaneous	0.6	same
11	12.26	3.3	26	instantaneous	0.6	"
12	12.28	4.4	29	instantaneous	0.6	"
13	12.30	2.2	29	60	0.6	"
14	12.32	3.3	27	60	0.6	"
15	12.35	4.4	28	60	0.6	"

12:45, the spine of the monkey, still under narcosis, is severed by scalpel /5
suboccipitally.

Position 1 (1st position). Centrifugal forces act in the head-to-leg direction; the experimental animal is lying with its head toward the axis of rotation.

Position 2 (2nd position): The centrifugal forces act in the stomach-to-back direction; the animal is lying with its stomach toward the axis of rotation.

The procedure of experiment #9 follows as an example: R. 11. exp. 9. Monkey experiment 5/2/37. Macacus rhesus, old male, weight 5.8 kg. 9:29 AM. 1.8 cc permoctane for anesthesia i.m. 10:00. Monkey lies peacefully in cage, still not asleep. 10:10. since the monkey is still not asleep, an additional 4. cc pernocton given i.m. 11:40. operation on the left side of the throat for exposure of the internal jugular vein. 11:50. injection of 80 cc. thoratrast in exposed vein, injection time 225 seconds. 12:00. Injection finished. 12:04 operation completed.

RESULTS

When a comparative evaluation of the x-ray films is made, the change in the heart filling is immediately perceived. Figures 4 through 7 show the x-ray photographs of a monkey in the side position. The centrifugal force is acting in the head-to-leg direction. Figure 4 is a picture taken at rest; the filling is normal; the borders are clearly evident; the aorta and inferior vena cava are also visible. Figure 5 shows the same test animal at an acceleration of 2.2 G. The shadow of the heart and of the vessels directed cranially have clearly become lighter. The outline of the heart is unclear in the area of the apex. In comparison with the other picture, the heart-filling may be designated medium (intermediate). It is already extremely poor in Figure 6 for the test animal at an acceleration of 4.4 G. Here the shadow of the heart is very faint and small, and no clear outline can be perceived. The ascending aorta shows up most clearly while the descending aorta and vena cava are barely visible. Figure 7 was taken at an acceleration of 6.6 G. The heart is practically empty and its shadow and the shadow of the large vessels are barely discernible.

TABLE 2. HEART FILLING WITH CENTRIFUGAL FORCES ACTING IN A HEAD-TO-LEG DIRECTION

	Rest	2.2 G	3.3 G	4.4 G	5.5 G	6.6 G	7.7 G
Number of Pictures	15	14	6	8	2	5	2
Good filling	15	8	2	—	--	—	—
Medium filling	—	6	33	—	--	—	—
Poor filling	—	—	1	4	1	2	—
Empty	—	—	—	4	1	3	2

Figures 4 through 7 show that when acceleration increases, the filling of /6
the heart decreases until it is practically zero if the centrifugal forces act in the head-to-leg direction. The rate and amount of decrease in filling at the separate accelerations depend on the physical state of the individual experimental animals. One consistent finding in all the experimental animals is that at increasing accelerations between 3 and 5 G with the centrifugal forces acting in the head-to-leg direction, the filling of the heart decreases until it is completely empty at 6.6 G.

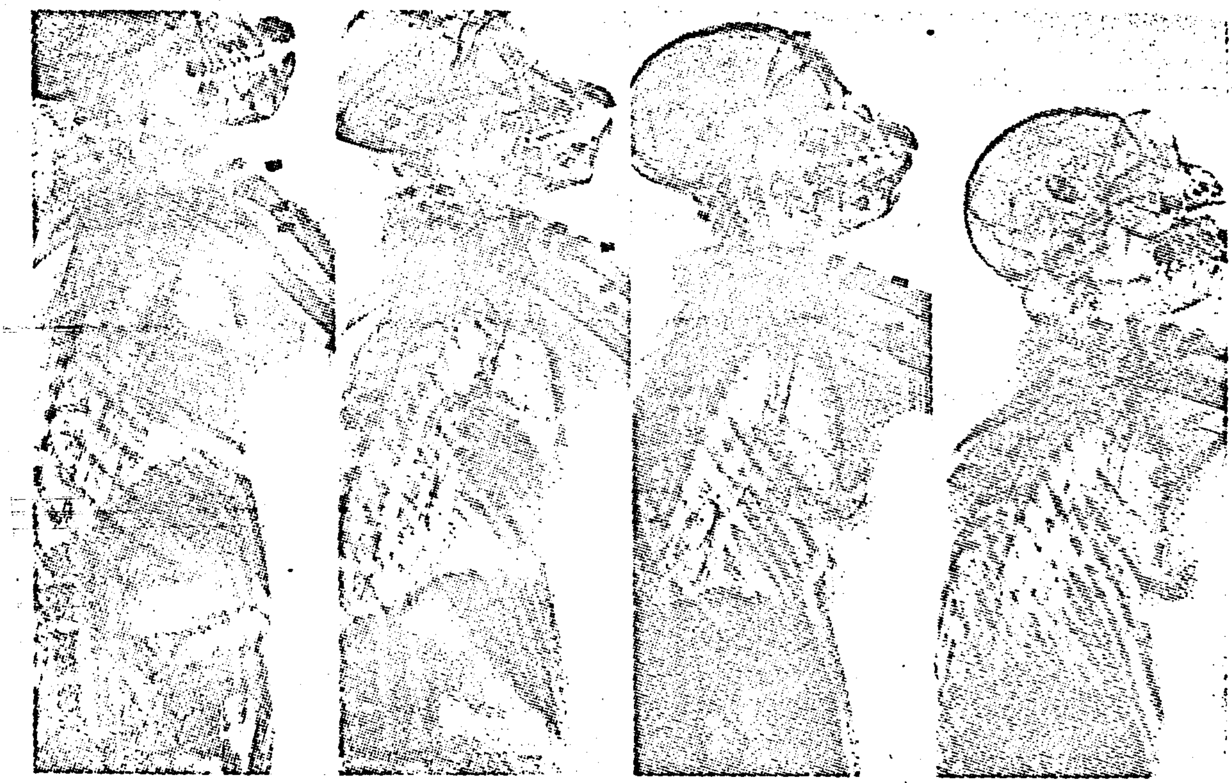

Figure 4 (exp. 3/2). Figure 5 (exp. 3/3). Figure 6 (exp. 3/4). Figure 7. (exp. 3/5).
Acceleration: 0. 2.2 G. 4.4 G. 6.6 G.

Figures 4 through 7. Monkey under pernokton narcosis. Weight 4.4 kg. Decrease in heart filling at increasing accelerations. Centrifugal force in head-to-leg direction. /6

The table given on page 5 again shows the above-described relationship /7 between increasing acceleration and decreasing heart-filling, with centrifugal force in the head-to-leg direction. Only those pictures were evaluated in which the test animal had not been kept at too high or too long-lasting accelerations.

Figures 8 and 9 show that the phenomena observed in the heart also occur in the large vessels. Figure 8 shows a monkey at an acceleration of 2.2 G; figure 9 shows the same animal at 3.3 G. Not only is the shadow of the vessels weaker (aorta and inferior vena cava) in figure 9, but the diameter of these vessels has grown smaller corresponding to the reduced filling. The conclusions concerning the effect on the blood pressure will be contained in a paper soon to follow this one.

In the experiments discussed above, the pictures were taken immediately after the desired acceleration had been attained by the centrifuge, while in another series of experiments, the pictures were taken after the test animal had been exposed to acceleration for some time.

Figure 10 shows a normal picture taken at rest. In Figure 11, the picture /8

Figure 8 (exp. 10/6). Acceleration 2.2 G.

Figure 9 (exp. 10/7). 3.3 G.

was taken immediately after 3.3 G had been reached on the centrifuge. In Figure 12, 3.3 G has been in effect for 1 minute, in Figure 13, 2 minutes, before the corresponding pictures were taken. Figures 10 through 13 show clearly that the decrease in heart filling is not only caused by the amount of acceleration but that the prolongation of the time of exposure to acceleration has a similar effect on heart filling as does an increase in acceleration. /9

The filling of the heart is not the only thing to change when the centrifugal forces act in the head-to-leg direction; the position of the heart in the chest cavity also changes. If one compares Figures 4 through 7, it becomes apparent that the heart position becomes increasingly longitudinal causing the apex to sink lower as acceleration is increased. This relationship between increasing acceleration and lowering of the apex is shown by the curves in Figure 14. The first 5 experiments were used to obtain these values. Only the solid lines are important. Whereas the apex is normally at the level of the 9th thoracic vertebra, it drops at high accelerations and usually extends as far as the 12th vertebra at 4.4 to 7.7 G; in one case at 6.6 G it reached the 1st lumbar vertebra. The corresponding displacement of the diaphragm fundus, due to flattening, is likewise apparent from Figures 4 through 7.

It is natural for the form of the heart to change with its filling. This

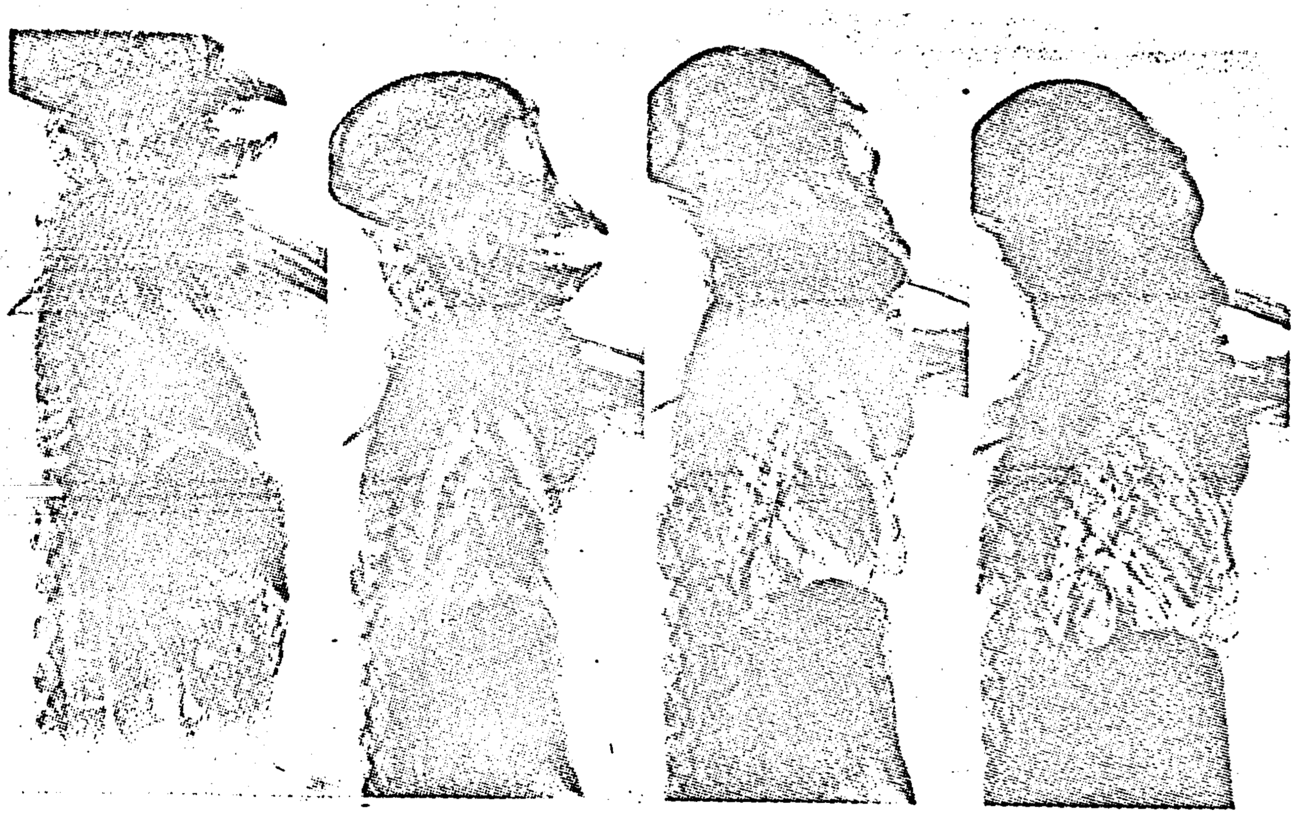

Figure 10(Exp. 10/2).Figure 11(Exp. 10/4).Figure 12(Exp. 10/7).Figure 13(Exp. 10/9)

Figures 10-13. Monkey under Pernokton narcosis, weight 3.8 kg, decrease in heart filling during prolonged exposure to acceleration. Centrifugal force acts in head-to-leg direction.

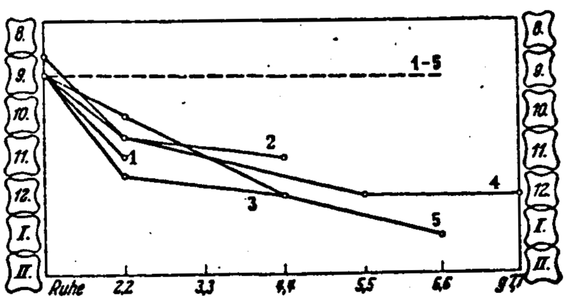

Figure 14

is shown in Figures 15 through 18. A picture at rest (Figure 15) and pictures at 2.2 G (Figure 16), 3.3 G (Figure 17), and 4.4 G (Figure 18) were taken of a monkey in the back position. The centrifugal forces are acting in the head-to-leg direction. It is evident that as acceleration increases, the heart shadow becomes increasingly narrower until it disappears in the shadow of the spinal column as is shown by Figure 18 which is not technically perfect.

Thus it has been shown that strong centrifugal forces in the head-to-leg direction disturb the distribution of the blood. The question still remains of how the circulation behaves if the centrifugal forces act in another direction.

Figures 20 through 22 show a monkey in the side position with the centrifugal forces acting in the stomach-to-back direction at accelerations of 2.2 G,

TABLE 3. HEART FILLING WHE THE CENTRIFUGAL FORCES ARE ACTING IN THE STOMACH-TO-BACK DIRECTION

	Rest	2.2 G	4.4 G	5.5 G	6.6 G
Number of Pictures...	6	3	4	1	3
Good filling	6	3	2	1	2
Medium filling	—	—	2	—	1
poor filling	—	—	—	—	—
Empty	—	—	—	—	—

4.4 G, and 6.6 G. Figure 19 is a picture taken at rest of the same animal and serves for purposes of comparison. A close look at Figures 19 through 22 also reveals a decrease in heart filling, but in comparison to that seen in the experiments with the centrifugal forces acting in the head-to-leg direction, it is very slight. Wheras in the latter case, the heart filling at 4.4 G was at least poor, and often the heart was practically empty (compare with Figure 6), in this case, at 4.4 G, a filling is seen that is generally quite good. The difference becomes even more apparent if Figures 7 and 22, both taken at an acceleration of 6.6 G, are compared. /10

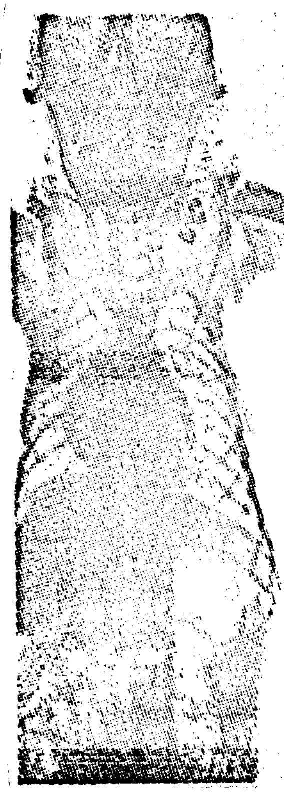

Figure 15 (Exp. 4/1) Acceleration 0

Figure 16 (Exp. 4/2 2.2 G.

Figure 17 (Exp. 4/3 5.5 G.

Figure 18 (Exp. 4/4 7.7 G.

Figures 15 through 18. Monkey under pernokton narcosis; 4.4 kg weight. Change in shape of the heart at increasing accelerations. Centrifugal forces acting in the head-to-leg direction.

Even at the highest acceleration, 10 G, attained in this series of experiments, there was no essential decrease in heart filling as can be seen by comparing Figure 24 with Figure 23, taken at rest.

Corresponding to the experiments summarized in Table 2 on the filling state /11
of the heart with centrifugal forces acting in the head-to-leg direction Table 3 shows the effects of centrifugal forces in the stomach-to-back direction. It confirms that which already been made clear by Figures 19 through 24.

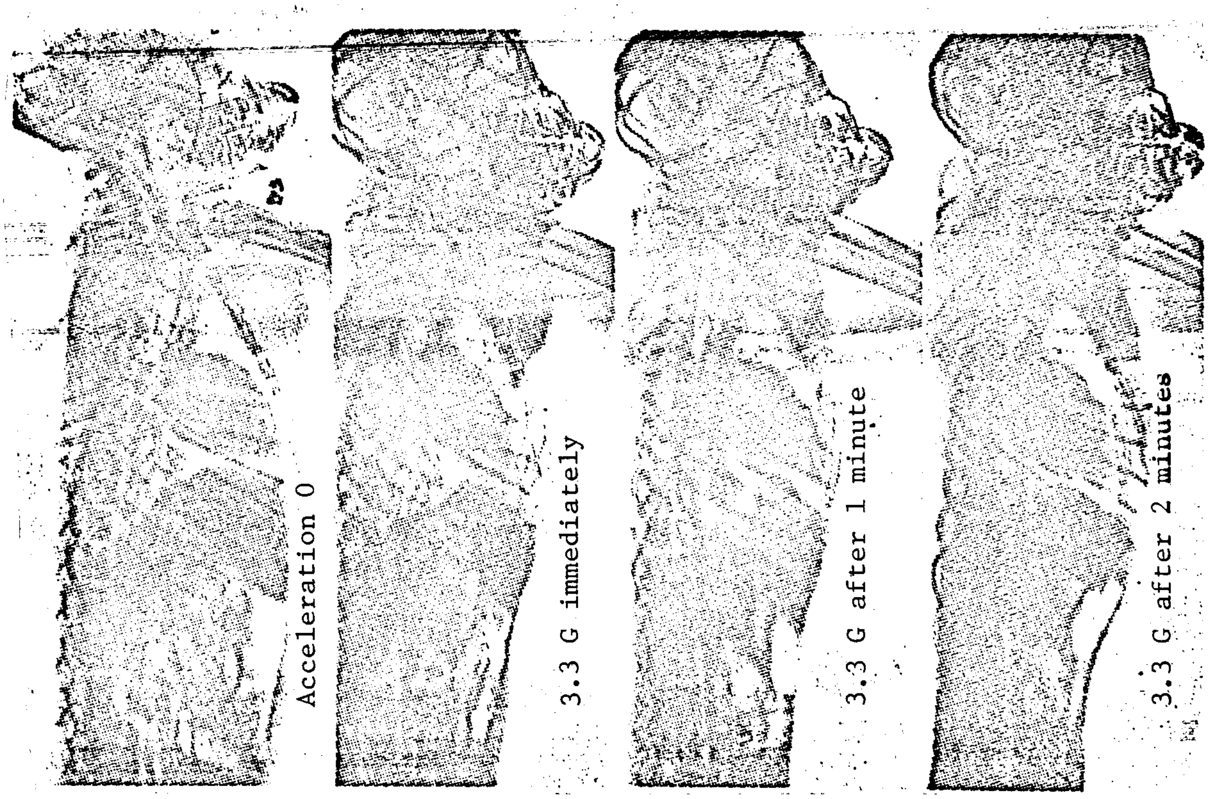

Figure 19(Exp.5/3) Figure 20(Exp.5/9) Figure 21(Exp.5/10) Figure 22(Exp.5/11)

Figures 19 through 22. Monkey under pernokton narcosis. Weight 3.4 kg. Heart-filling with centrifugal forces acting in the stomach-to-to-back direction.

When the experimental animal is in this position, blood displacement occurs in the direction of centrifugal-force, from the front section of the body into the dorsal thorax, causing a strong overfilling in this region.*

It was further established that even long exposure to the affects of /12
acceleration, when the centrifugal force acts in the stomach-to-back direction, have significantly less effect on heart filling than is the case when the centrifugal force acts in the head-to-leg direction.

The level of the heart also does not change when centrifugal force acts in the stomach-to-back direction. Figure 14 contains, besides the representation of the lowering of the apex when the centrifugal force acts in the head-to-leg direction (solid lines), the position of the apex when centrifugal

*Prof. Ranke was able to exclude hemorrhage in experiments not yet published.

force is in the stomach-to-back direction (broken line). In the latter case, the first 5 experiments were evaluated and showed the same results, namely that the position of the apex does not change despite increasing accelerations (compare also Figures 19 through 22).

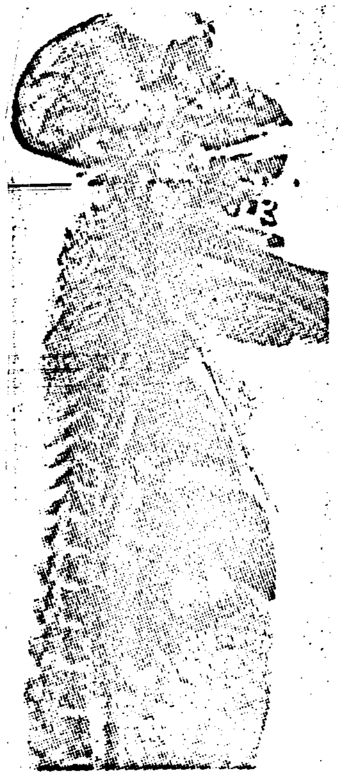

Figure 23 (Exp. 11/5
Acceleration 0

Figure 24 (Exp. 11/7
10 G

Figures 23 and 24. Monkey under pernokton narcosis. Weight 3.2 kg. Heart filling at high accelerations; centrifugal forces act in the stomach-to-back direction.

The only perceptible change in the heart position in the chest cavity during high accelerations was a slight displacement toward the spinal column. No circulation disturbances, if any, could be detected on the x-ray photos.

SUMMARY /13

1. Acceleration experiments were performed on the centrifuge of the Aeromedical Research Institute of the National Air Ministry using 10 monkeys, (Macacus rhesus) after injections of thorotrast so that x-ray photographs could be taken on a concurrently operating x-ray device.

2. If the centrifugal forces act in the head-leg direction, the filling of the heart decreases with increasing acceleration, and at the same time the heart is rotated and forced downwards. Only traces of the x-ray contrast medium could be found in the heart at accelerations above 4.4 G.

3. The cross-section of the aorta and inferior vena cava decreased as the heart became empty.

4. While 1 or 2 minutes at 3.3 G are required before the heart becomes empty, at 4.4 G the heart is empty in a few seconds. Not only the amount of acceleration but its duration affect the decrease in heart filling.

5. The endurance of the animals differs according to their physical condition.

6. If the centrifugal force acts in the stomach-to-back direction, the heart filling remains good up to the highest acceleration attained (10 G). Exposures to 6.6 G for up to 1 minute change the circulation only by forcing the heart up against the spinal column and the increasing blood filling of the posterior sections of the thorax.

7. The results are depicted on 20 x-ray photographs, 2 tables, and 1 graph.

I would like at this point to express my most profound gratitude to my honorable teacher, Staff Physicial Prof. Dr. Otto F. Ranke for assigning this work and for the friendly support he gave at all times.

LITERATURE

1. Schubert: Human Physiology in the Aircraft (Physiologie des Menschen im Flugzeug), conjointly with a compilation of literature, Julius Springer, Berlin, 1935.
2. von Diringshofen: Luftfahrtmedizin, Vol. 1, No. 3, p. 226.
3. Jongbloed and Noyons: Pflugers Archiv, Vol. 233, No. 1.
4. Koch: The Reflexive Autoregulation of the Circulation (Die reflektorische Selbststeurerung des Kreislaufs). Theodor Steinkopff, Dreseen-Leipzig, 1931.
5. Eppinger, Kaunitz, and Popper: Serous Inflammation (Die serose Entzundung). Julius Springer, Vienna, 1935.
6. Bohme, W.: Klin. Wschr., p. 614, I, 1935: Röntgenstrahlen, Vol. 52, Kongrefn., p. 36: Roentgenkymographic Theory of motion of the Internal organs (Rontgenkymographische Bewegungslehre innerer Organe). Leipzig p. 222, 1936. Rousthoi, Peter: Acta med. scand. (Stockholm), Vol. 59, p. 558, 1937. Menkes and Benedikt: Fortschr. Rntgenstr., Vol. 48, No. 2, p. 204, 1933.
7. Bührlen: Luftfahrtmedizin, Vol. 1, No. 5.
8. Ranke: 14. Tagg. dtsch. Physiol. Ges. Giessen, Ber. Physiol., Vol. 96, p. 671.

Translation prepared for the National Aeronautics and Space Administration by INTERNATIONAL INFORMATION INCORPORATED, 2101 Walnut St., Philadelphia, Pa. 19103 Contract No. NASw-1499.